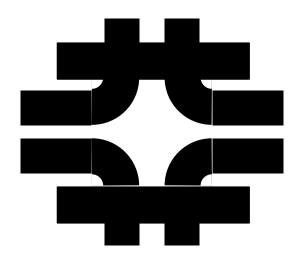
RADIATION PHYSICS FOR PERSONNEL AND ENVIRONMENTAL PROTECTION

J. DONALD COSSAIRT FERMI NATIONAL ACCELERATOR LABORATORY



US PARTICLE ACCELERATOR SCHOOL Florida State University-1993 Duke University-1995 University of California, Berkeley-1997 Vanderbilt University-1999 Rice University-2001

TM-1834 Revision 6, February 2003

Indiana University-2003

ACKNOWLEDGMENTS

This text is dedicated to my wife Claudia, and our children, Joe and Sally, who provided me with love, cheerfulness, and their support during the long hours spent in the preparation of this and preceding versions of this text. I acknowledge the opportunity provided by Fermilab Director J. Peoples, Jr., to initially participate in the U. S. Particle Accelerator School. The support of my teaching in the USPAS by M. Month, S. Y. Lee, H. Wiedemann, A. L. Read, and W. Griffing has been sincerely appreciated. Members of the Fermilab Environment, Safety and Health Section have greatly assisted me during the preparation and revision of these materials. A. Elwyn deserves special recognition for his helpful advice during the preparation of this text and, indeed, during his entire distinguished career at Fermilab in which he, in so many ways, has been my scientific mentor. N. Grossman, K. Vaziri, V. Cupps, R. Ronningen (National Superconducting Cyclotron Laboratory at Michigan State University) and S. Schwahn (Thomas Jefferson National Accelerator Facility) have provided me with very constructive criticism in connection with their assistance in presenting these materials to students in the USPAS. Others at Fermilab whose comments have been helpful are D. Boehnlein, K. Graden, P. Kesich, E. Marshall, and W. Schmitt.

> J. Donald Cossairt February 2003

PREFACE

The original version of this text was presented as part of a course taught at session of the U. S. Particle Accelerator School held at Florida State University in January 1993. Subsequently, the material was further refined and presented as a course at Fermilab in the spring of 1993 and autumn of 1994. Later, the course was presented at the USPAS sessions held under the auspices of Duke University (January 1995), the University of California, Berkeley (January 1997), Vanderbilt University (January 1999), Rice University (January 2001), and Indiana University (January 2003). Comments received from the many students have been very helpful in the continued development of this course, and hopefully in its improvement. This sixth revision represents a compilation of the work of numerous people and it is hoped that the reference citations lead the reader to the original work of those individuals who have developed this field of applied physics. Over the years, I have been greatly enriched by being personally acquainted with many of these fine scientists. The problems supplied with each chapter were developed with the goal of promoting better understanding of the text.

Chap	oter 1 B	Sasic Radiation Physics Concepts and Units of Measurement		
1.1	Introd	luction	1-1	
1.2		Review of Units, Physical Constants, and Material Properties		
	1.2.1	Radiation Physics Terminology and Units	1-1	
	1.2.2	•	1-8	
1.3		nary of Relativistic Relationships	1-11	
1.4		Energy Loss by Ionization and Multiple Coulomb Scattering		
	_	Energy Loss by Ionization	1-12 1-12	
		Multiple Coulomb Scattering	1-18	
1.5		ological Standards	1-19	
Prob			1-20	
Chap	oter 2 G	General Considerations of Radiation Fields at Accelerators		
2.1	Introd	luction	2-1	
2.2		ry Radiation Fields At Accelerators-General Considerations	2-1	
2.3		ry of Radiation Transport	2-3	
	2.3.1 General Considerations of Radiation Transport			
		The Boltzmann Equation	2-3 2-4	
2.4		Monte Carlo Method	2-6	
2	2.4.1 General Principles of the Monte Carlo Technique			
	2.4.2	1	2-6	
		of Beam Particles	2-9	
2.5	Review of Magnetic Deflection and Focussing of Charged Particles		2-11	
		2.5.1 Magnetic Deflection of Charged Particles		
	2.5.2		2-11 2-13	
Probl			2-20	
Chap	oter 3 P	Prompt Radiation Fields Due to Electrons		
3.1	Introd	luction	3-1	
3.2	Unshi	elded Radiation Produced by Electron Beams	3-1	
	3.2.1	3.2.1 Dose Equivalent Rate in a Direct Beam of Electrons		
	3.2.2	Bremsstrahlung	3-2	
	3.2.3	<u> </u>	3-7	
	3.2.4	· ·	3-9	
		3.2.4.1 Giant Photonuclear Resonance Neutrons	3-9	
		3.2.4.2 Quasi-Deuteron Neutrons	3-11	
		3.2.4.3 Neutrons Associated with the Production of Other	-	
		Particles	3-12	
	3.2.5		3-12	
	3.2.6	Summary of Unshielded Radiation Produced by Electron		
	2.2.0	Beams	3-14	
3.3	The F	Electromagnetic Cascade-Introduction	3-15	
3.4	The Electromagnetic Cascade Process			

3.5	3.4.2 Shield 3.5.1 3.5.2	Longitudinal Shower Development Lateral Shower Development ling of Hadrons Produced by the Electromagnetic Cascade Neutrons High Energy Particles	3-19 3-22 3-24 3-24 3-25
Proble	ms		3-27
Chapt	er 4 P	rompt Radiation Fields Due to Protons and Ions	
4.1	Introd	uction	4-1
4.2	Radiation Production by Proton Accelerators		
	4.2.1	The Direct Beam; Radiation and Nuclear Interactions	4-1
	4.2.2	`	4-1
		4.2.2.1 $E_o < 10 \text{ MeV}$	4-3
		$4.2.2.2 10 < E_o < 200 \text{ MeV}$	4-3
		4.2.2.3 200 MeV $< E_o < 1$ GeV; ("Intermediate" Energy)	4-6
		4.2.2.4 $E_O > 1$ GeV ("High" Energy Region)	4-6
	4.2.3	Sullivan's Formula	4-10
	4.2.4	Muons	4-12
4.3	Primary Radiation Fields at Ion Accelerators		4-12
		Light Ions (Ion Mass Number, $A < 5$)	4-13
		Heavy Ions (Ions with $A > 4$)	4-13
4.4	Hadron (Neutron) Shielding for Low Energy Incident Protons		
		15 MeV)	4-18
4.5		ng Attenuation at High Energy	4-20
4.6		nediate and High Energy Shielding-The Hadronic Cascade	4-23
		The Hadronic Cascade from a Conceptual Standpoint	4-23
		A Simple One-Dimensional Model	4-24
		Semiempirical Method, the Moyer Model for a Point Source	4-28
4.7	4.6.4	•	4-31
4.7	The Use of Monte Carlo Shielding Codes for Hadronic Cascades		4-34
	4.7.1	Examples of Results of Monte Carlo Calculations Canada Carraga Carr	4-34
	4.7.2 4.7.3	General Comments on Monte Carlo Star-to-Dose Conversions	4-38 4-40
Proble		Shielding Against Muons at Proton Accelerators	4-40 4-46
FIODIC	1115		4-40
Chapt	er 5 L	ow Energy Prompt Neutron Radiation Phenomena	
5.1	Introd	uction	5-1
5.2		mission of Photons and Neutrons Through Penetrations	5-1
	5.2.1	Albedo Coefficients	5-1
		5.2.1.1 Usage of Photon Albedo Coefficients	5-4
	5.2.2		
		-General Considerations	5-6
	5.2.3	Attenuation in Straight Penetrations or the First Leg of	
		Rectilinear Penetrations	5-7

5.3	5.2.7 Skysh 5.3.1 5.3.2 5.3.3	Attenuation in Curved Tunnels Attenuation Beyond the Exit Determination of the Source Factor ine	5-11 5-16 5-16 5-18 5-19 5-19 5-21 5-26 5-30	
Chap	ter 6 S	hielding Materials and Neutron Energy Spectra		
6 1	Introd	wation	6-1	
6.1 6.2		ssion of Shielding Materials Commonly Used at Accelerators	6-1	
0.2	6.2.1	Earth	6-1	
	6.2.2	Concrete	6-2	
	6.2.3	Other Hydrogenous Materials	6-3	
		6.2.3.1 Polyethylene and other Materials That Can Be Borated	6-3	
		6.2.3.2 Water, Wood, and Paraffin	6-4	
	6.2.4	Iron	6-5	
	6.2.5		6-5	
<i>c</i> 2	6.2.6	Miscellaneous Materials (Beryllium, Aluminum, and Zirconium)	6-6 6-6	
6.3	Neutron Energy Spectra Outside of Shields 6.3.1 General Considerations			
	6.3.1	Example of Neutron Spectra Due to Incident Electrons	6-6 6-7	
	6.3.3	Examples of Neutron Spectra Due to Low and Intermediate	0-7	
	0.5.5	Energy Protons	6-9	
	6.3.4		6-9	
	6.3.5	1 0 0,	6-16	
	6.3.6	Neutron Spectra Due to Ions	6-19	
	6.3.7	Neutron Fluence and Dosimetry	6-21	
Chap	ter 7 In	nduced Radioactivity in Accelerator Components		
7.1	Introd	uction	7-1	
7.1			7-1 7-1	
7.3		Fundamental Principles of Induced Radioactivity Activation of Components at Electron Accelerators		
7.5	7.3.1	-	7-3 7-3	
		Results for Electrons at Low Energy	7-4	
		Results for Electrons at High Energy	7-8	
7.4		ation of Accelerator Components at Proton and Ion Accelerators	7-13	
		General Phenomena	7-13	
	7.4.2	Methods of Systematizing Activation Due to High Energy		
		Hadrons	7-21	
		7.4.2.1 Gollon's Rules of Thumb	7-26	

	7.4.3	The Utilization of Monte Carlo Star Densities in Activation	
		Calculations	7-32
	7.4.4	Uniform Irradiation of the Walls of an Accelerator Enclosures	7-35
Proble	ms		7-38
Chapt	er 8 In	duced Radioactivity in Environmental Media	
8.1	Introdu	action	8-1
8.2	Airbor	ne Radioactivity	8-1
		Production	8-1
	8.2.2	Accounting for Ventilation	8-2
	8.2.3	Propagation of Radionuclides in the Environment	8-4
		8.2.3.1 Propagation of Radioactivity - Tall Stacks	8-4
		8.2.3.2 Propagation of Airborne Radioactivity - Short Stacks	8-7
	8.2.4	Radiation Protection Standards for Airborne Radioactivity	8-8
	8.2.5	Production of Airborne Radionuclides at Electron Accelerators	8-12
	8.2.6	Production of Airborne Radionuclides at Proton Accelerators	8-14
8.3	Water	and Geological Media Activation	8-15
	8.3.1	Water Activation at Electron Accelerators	8-15
	8.3.2	Water and Geological Media Activation at Proton Accelerators	8-17
		8.3.2.1 Water Activation	8-17
		8.3.2.2 Geological Media Activation	8-17
	8.3.3	Regulatory Standards	8-21
	8.3.4	The Propagation of Radionuclides Through Geological Media	8-23
Proble	ms		8-30
CI 4	0 D		
Cnapt	er y Ka	adiation Protection Instrumentation at Accelerators	
9.1	Introdu	action	9-1
9.2	Counti	ng Statistics	9-1
9.3	Specia	l Considerations for Accelerator Environments	9-4
	9.3.1	Large Range of Flux Densities, Absorbed Dose Rates, etc.	9-4
	9.3.2	Possible Large Instantaneous Values of Flux Densities, Absorbed	
		Dose Rates, etc.	9-4
	9.3.3	Large Dynamic Range of Neutron Radiation Fields	9-4
	9.3.4	Presence of Mixed Radiation Fields	9-4
	9.3.5	Directional Sensitivity	9-5
	9.3.6	Sensitivity to Features of the Accelerator Environment Other	
		Than Ionizing Radiation	9-5
9.4	Standa	rd Instruments and Dosimeters	9-5
	9.4.1	Ionization Chambers	9-5
	9.4.2	Geiger-Müller Detectors	9-9
	9.4.3	Thermoluminescent Dosimeters (TLDs)	9-10
	9.4.4	Nuclear Track Emulsions	9-11
	9.4.5	Track Etch Dosimeters	9-11
	9.4.6	CR-39 Dosimeters	9-11

	0.47	D 111 D	0.10
	9.4.7	Bubble Detectors	9-12
9.5	Specialized Detectors		9-12
	9.5.1	Thermal Neutron Detectors	9-12
		9.5.1.1 Boron-10	9-14
		9.5.1.2 Lithium-6	9-15
		9.5.1.3 Helium-3	9-15
		9.5.1.4 Cadmium-113	9-17
		9.5.1.5 Silver	9-17
	9.5.2	Moderated Neutron Detectors	9-17
		9.5.2.1 Spherical Moderators, Bonner Spheres, and Related	
		Detectors	9-18
		9.5.2.2 Long Counters	9-26
	9.5.3	Activation and Threshold Detectors	9-27
	9.5.4	Fission Counters	
	9.5.5	Proton Recoil Counters	
	9.5.6	TEPCs and LET Spectrometry	
	9.5.7	Recombination Chambers	
	9.5.8	Counter Telescopes	9-37
Probl	lems		9-39

Appendix A Summary Descriptions of Commonly Used Monte Carlo Codes

Appendix B Examples of Results of Star Density Calculations Using CASIM

References

Table of Contents	